Modeling and Control of a Solid Oxide Fuel Cell Auxiliary Power Unit

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Objectives

- Task 1: Develop a dynamic system model of a solid oxide fuel cell (SOFC) based auxiliary power unit (APU) and design a system controller to minimize diesel fuel consumption, maximize operating lifetime and satisfy electrical load requirements for Class VIII truck applications.
- Task 2: Develop analytical models and perform testing to determine the dynamic structural response and vibrational limits of SOFC-based APU systems in a Class VIII truck operational environment.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year R,D&D Plan:

- C. Thermal Management
- D. Fuel Cell Power System Benchmarking
- H. Startup Time
- P. Durability

Approach

Task 1

- Create a dynamic, electro-chemical model of the SOFC stack.
- Create dynamic balance of plant component, operational models using theoretical first principles and experimental data.
- Create a system functionality model by combining component models.
- Design controllers using the model to optimize fuel efficiency and lifespan.
- Verify models through experimental testing and collaboration. Collect actual Class VIII truck electrical load profiles with PACCAR and test APU systems with Delphi.

Task 2

- Develop a lumped parameter model to determine the vibration amplitude of the SOFC stack due to base excitation of the APU.
- Perform stress analysis on a detailed finite element model of a multiple-cell planar SOFC stack using the stack loading history.
- Develop failure models for Positive-Electrolyte-Negative (PEN) cell fracture and seal interfacial separation to define APU vibrational limits and isolation requirements for stack durability.

- Collect data in collaboration with PACCAR for actual vibration loads of a truck-mounted APU.
- Perform dynamic testing of an APU and components for fundamental material data and model validation.

Accomplishments

Task 1

- Creation of APU system and component models: electro-chemical model of the SOFC stack, diesel fuel reformer, exhaust gas combustor and heat exchangers.
- Completion of a dynamic model of a truck heating and air-conditioning system, including inrush current at startup and driver heat input.
- Assembly of controllers to regulate cathode air temperature during heat-up phase to prevent thermal shock to SOFC and fuel flow rate control under varying electrical load.

Task 2

- Reviewed standards for shock and vibration testing and electronic equipment design for heavy trucks to establish a basis for the dynamic loading environment.
- Created lumped parameter model in ANSYS to determine influence of APU components on stack dynamic response.
- Detailed finite element model of SOFC stack to determine resonant frequencies and dynamic stresses due to harmonic excitation.
- Identified method to define a vibrational limit spectrum to prevent stack failure.

Future Directions

Task 1

- Create high level, optimized controllers to maximize fuel efficiency and device lifespan.
- Improve dynamic models. Focus on the SOFC stack response to dynamic inputs (such as fuel flow rate changes and temperature changes) through collection of experimental data on single cell SOFCs.
- Model un-measurable inner parameters of SOFC stack.
- Improve power conversion electronics modeling through collaboration with University of Illinois, Chicago.
- Collect actual electrical system load profiles in Class VIII trucks with PACCAR.
- Test realism of control strategies for APU system in partnership with Delphi.

Task 2

- Complete failure model development for PEN fracture and interfacial separation.
- Incorporate spectral solution methods.
- Develop procedure to analyze shock and impact loading of the APU.
- Perform parametric analysis for various SOFC and APU designs.
- Collect actual truck shock and vibration data in collaboration with PACCAR.
- Determine fundamental properties for cell materials under dynamic loading.
- Perform experimental testing of SOFC and APU components in collaboration with Delphi.

Introduction

Long-haul trucks require electrical power to operate hotel loads (lights, heating/air conditioning and televisions) while parked for the operator to rest. Typically, these loads are powered by idling the engine or, less commonly, with a dedicated diesel generator based auxiliary power unit (APU). Fuel cell based APUs hold the promise of greater energy efficiency, lower operating costs, lower emissions, and quiet operation. A solid oxide fuel cell (SOFC) is expected to be the choice for transportation applications because 1) it has higher power density than other designs to minimize stack mass and volume and 2) it offers fuel flexibility due to its high operation temperatures and toleration of impurities.

This project looks at modeling of SOFC APUs to understand how design choices impact efficiency and durability. This work is the first step towards full electrification of the truck when the engine is used solely for propulsion and today's belt driven pumps and fans are run off electricity from the APU. Task 1 investigates operational models of APU components and the entire system to show how the devices interact, and different configurations are investigated for increased fuel efficiency. The operational models allow the creation of effective control strategies to optimize fuel efficiency and long lifespan. Task 2 provides modeling tools to evaluate the dynamic thermal-mechanical stresses in the stack. The high temperature and dissimilar materials make SOFC structural robustness challenging when it must also withstand the rigorous dynamic loading of a heavy truck. The models will allow designers to define appropriate materials, cell design, physical layout, and isolation components to minimize vibrational loads to acceptable levels for increased durability in real applications.

Approach

Task 1: The approach to creating operational models of the APU components and system has been to combine theoretical operation with experimental data, keeping the models broadly applicable but realistic. Electrical load profiles from Class VIII trucks will be collected with PACCAR to understand how APUs are used in practice. Models for components such as the diesel partial oxidation (POX) reformer, heat exchangers and SOFC stack are created in a modular environment that allows them to easily be connected in different configurations. This allows different fuel and thermal management strategies to be tested. Work on the controller has begun, with independent control of individual components. This will be followed by higher level controllers, coordinating all components and increasing fuel efficiency. Finally, as the model matures, it will be possible to optimize control to minimize fuel consumption, maximize lifespan and meet electrical load requirements.

Task 2: The commercial finite element code ANSYS was used to model the APU system response at three levels. For the first model, the APU was simplified to a small number of major components. Based on mass and stiffness properties of the components and connections, the dynamic loading imparted to the stack due to base excitation of the APU could be calculated across the frequency range of interest. This was used as input to a detailed model of the SOFC stack, which computes the deformation and stresses of the cells due to harmonic excitation. Stress analysis results can be compared to strength of the constituent materials to determine allowable excitation amplitudes. Fracture must be considered for brittle materials like the ceramic PEN and rigid seals. Finite element models to study anode cracks and interfacial seal separation are under development and will be similarly used to determine allowable excitation amplitudes. Parametric analysis will then be performed to identify critical elements in APU and stack design. Collection of actual excitation loads and experimentally testing of the SOFC components and APU will benchmark the models to ensure they are usable in real truck and transportation applications.

Results

The scope of this research project is to create models and controllers that provide design guidelines for SOFC-based APU applications. The models provide information about what conditions the SOFC APU will be subject to in operation and how it behaves. Models and controls are verified and augmented through experimental testing.

Task 1: To date, this research has produced operational models of the following APU components: POX reformers (both diesel and gasoline), combustor, heat exchangers and the SOFC stack. These models compute the chemical and thermal reactions inside each component. An example of the voltage-current (VI) output of the SOFC model for various stack temperatures is shown in Figure 1. Models of electrical loads such as the heating and air-conditioning system have also been created. These models have been connected to form a complete system for simulation of operations.

Using the component models, initial controllers have been developed. Currently, control is divided into two phases: startup and operating. The startup controller regulates the temperature of air blown over the stack to heat it to operating temperatures (around 700°C). The rate of temperature increase must be strictly regulated to prevent undue thermal stress to the stack that would shorten its operational lifespan. The operating controller ensures that sufficient fuel is reaching the stack to produce enough electricity to match the electrical load. As electrical load requirements decrease, fuel flow to the stack should also decrease, preventing waste and increasing fuel efficiency. An example of this controller is shown in Figure 2.

Task 2: Work for this year is exclusive to predictive model development and study of dynamic loading effects. Modal results for a planar stack indicate the fundamental frequency is due to out-of-plane vibration of the frame-supported PEN and the interconnect plate, depending on the interconnect stiffness as shown in Figure 3. Fundamental frequencies from thin plate theory and modal results for a stack model are shown in Figure 4, and they are much greater than typical engine speeds of 700-2100 rpm (12-35 Hz). An example curve for the permissible harmonic excitation of a five-cell stack is shown in Figure 5. Superposition of the elastic solutions for thermal-mechanical and dynamic stresses was used to predict the maximum amplitude based on a single criterion that the Mode I stress intensity factor for a 5 or 25 mm semicircular flaw at the anode surface be less than a critical stress intensity of 1.0 MPa-m1/2. The results indicate that a stack vibration of 1-4 G's can be critical, although this assumes that the flaw is at the location of maximum stress. The union of all potential failure

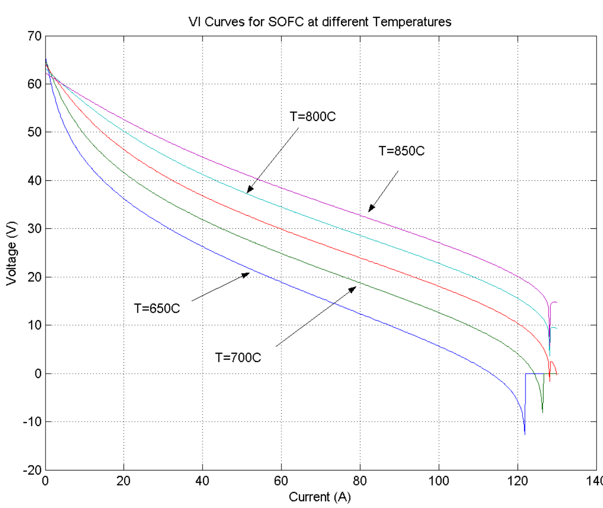

Figure 1. SOFC Voltage-Current Curves for Various Temperatures

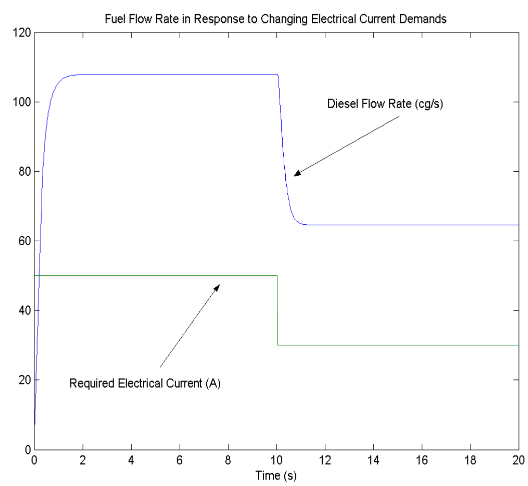

Figure 2. Fuel Flow Rate Response to Electrical Current Change

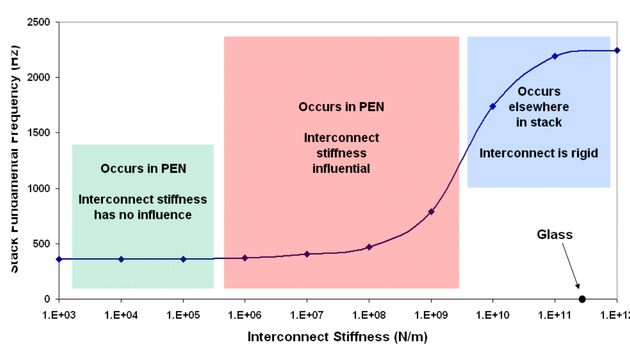

Figure 3. Variation of PEN Fundamental Frequency with Interconnect Stiffness

Component	Plate Theory (Hz)	Modal Analysis (Hz)
PEN	simple support 188 clamped 371	PEN: 370
Separator Plate	corner support 133 simple support 389 clamped 735	PEN & Separator Plate: 460

Figure 4. Fundamental Frequencies for SOFC Components from Thin Plate Theory and Modal Analysis

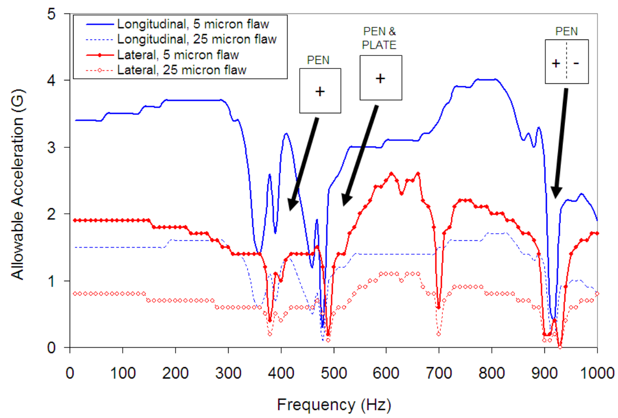

Figure 5. Permissible Longitudinal and Lateral Vibration Amplitudes for a Planar SOFC Stack

criteria with consideration of defect density would define the actual critical response curve. Interfacial separation of the PEN and seals is expected to be an important failure mechanism due to coefficient of thermal expansion mismatches. Interfacial fracture of dissimilar materials is inherently mixed mode (Mode I and Mode II are coupled), and stress intensity factors depend on material properties which depend on anode porosity and nickel content. Relations to determine elastic properties and stress intensity factors as a function of porosity and composition have been developed using the Mori-Tanaka method as shown in Figure 6 for the properties of the NiO/YSZ anode.

Conclusions

- Task 1: State-of-the-art models of an SOFC APU system and components were developed to describe the operational behavior of the APU. The models were used to develop controllers to

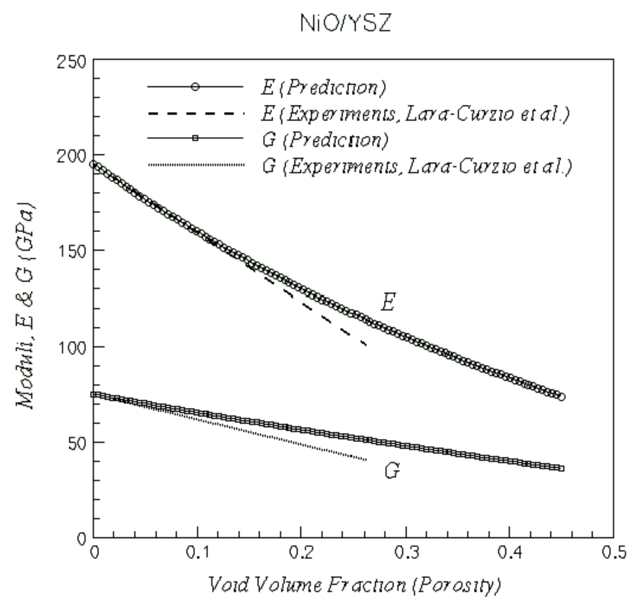

Figure 6. Comparison of Model and Experimental Results for Elastic Moduli of the NiO/YSZ Anode as a Function of Porosity

regulate fuel utilization under varying electrical loads and prevent thermal shock during heat up. Performance will be improved by creating higher level, optimized controllers and incorporating the results of experimental tests on single cell SOFC and APU systems in partnership with Delphi. Electrical load use profiles will be collected from real trucks with PACCAR, and detailed power electronic models will be made with University of Illinois, Chicago. Further models to describe full truck electrification will be done in collaboration with an engine manufacturer such as Caterpillar.

- Task 2: Finite element models constructed for dynamic analysis of a lumped parameter APU system and stress analysis of a detailed SOFC stack were used with a simple failure criterion to predict permissible vibration load as a function of frequency. For the future, continued improvement of the finite element analysis and failure models will provide wider applicability, truck dynamic loads will be determined with PACCAR to ensure realistic loading conditions, and APU/SOFC component testing will be done with Delphi to validate modeling efforts.

FY 2003 Publications/Presentations

1. M.A. Khaleel, B.J. Koeppel, and S.J. Moorehead, "Solid Oxide Fuel Cell Auxiliary Power Units for Long-Haul Trucks: Modeling and Control", Hydrogen, Fuel Cells & Infrastructure Technologies Program 2003 Merit Review and Peer Evaluation Meeting, Berkeley, CA (2003). Poster No. 96.